Ion Formation of *N*-Methyl Carbamate Pesticides in Thermospray Mass Spectrometry: The Effects of Additives to the Liquid Chromatographic Eluent and of the Vaporizer Temperature

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The effects of three additives—ammonium acetate, ammonium formate, and nicotinic acid—to the liquid chromatographic (LC) eluent and of the vaporizer temperature on the ion formation of *N*-methyl carbamate pesticides in thermospray (TSP) mass spectrometry was investigated by using filament- or discharge-assisted ionization. Nineteen carbamates and 12 of their known environmental degradation products were used as model compounds. The additives cause a strong reduction in the abundance of the characteristic fragment ions $[M + H - CH_3NCO]^+$ and $[M - H - CH_3NCO]^-$ for some of the carbamates. The addition of nicotinic acid reduces the quasimolecular ion intensity and, in most cases, produces nicotinic acid adduct ions. The addition of ammonium acetate or ammonium formate increases the intensity of the quasimolecular ion and in most cases produces a base peak for the ammonium adduct ion. The combination of a suppression of fragmentation and an enhancement of quasimolecular ion formation produces an overall gain in sensitivity. As to more specific effects, the addition of the ammonium salts reduces the intensity of $M^{-\bullet}$ with the chlorinated carbamate barban and suppresses the formation of "odd" adduct ions in the TSP mass spectra of most other carbamates. Monitoring the intensity of the fragment and the quasimolecular ion signal as a function of the probe stem temperature, and the related probe tip temperature, proved to be an easy method to study the thermal degradation of the carbamates. This monitoring procedure showed that methiocarb and its sulfone already suffer from thermal degradation at a stem temperature of 90 °C and that these compounds will therefore present problems in quantitation with LC/TSP mass spectrometry. *(J Am Soc Mass Spectrom 1994, 5, 913–927)*

In environmental analytical chemistry, the determination of polar pesticides and their even more polar degradation products is gaining in importance because of their toxicity and persistence [1–3]. Among these compounds the *N*-methyl carbamates and their degradation products are of particular interest.

The determination of the *N*-methyl carbamates by gas chromatography (GC) is seriously hampered by their thermolability, although recently Stan and Müller [4–6] obtained good results for some of these compounds by using a programmed temperature vaporizer injector. The GC determination of the usually demethylated, decarbamoylated, hydroxylated, or oxidized degradation products of the carbamates is complicated by low volatility and high polarity [7]. As a consequence, column liquid chromatography (LC) is frequently used to quantitate the carbamates as well as their degradation products. The Environmental Protection Agency procedure for the analysis of carbamates requires an LC system with post-column derivatization and fluorescence detection [8]. Similar types of procedures have been reported elsewhere [9,10]. If such LC procedures are combined with trace enrichment, quantitation is possible at very low concentrations (at the

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low parts per thousand level). However, these methods do not provide structural confirmation beyond the specificity of the derivatization reaction.

For the identification and quantitation of carbamates and their degradation products in environmental samples, liquid chromatography/mass spectrometry (LC/MS) with a thermospray (TSP) interface provides a promising option. However, because many parameters influence ion formation and signal stability in TSP, detailed knowledge about aspects that affect the analysis is required. The validity of this statement is corroborated by the fact that reported mass spectra of the carbamates, as obtained by the application of various ionization conditions (i.e., conventional chemical ionization (CI) [11–17] and LC/MS interfacing [18–34]), show large differences. This is illustrated by the data for carbofuran which are summarized in Table 1.

As can be seen, the intensity ratio of the ammonium adduct ion m/z 239 and the quasimolecular ion m/z 222 varies widely over the TSP mass spectra. Furthermore, the specific fragmentation required to produce m/z 165 from $[M + H]^+$ by loss of methyl isocyanate (CH_3NCO) [11] is observed with desorption CI, nebulizer assisted electrospray (ionspray), and atmospheric pressure chemical ionization (APCI) but not with TSP. Note that, for example, the ions m/z 165 may originate from different processes: thermal dissociation, dissociation of protonated molecules, or collision-induced dissociation. In all TSP experiments reported on carbofuran, ammonium acetate or ammonium formate was used as the carrier stream additive. Clearly there is no agreement on the quality of the spectra or on the ionization conditions.

Ion formation in TSP is often understood to be a mixture of gas-phase and liquid-phase processes. It was shown for pyridine, ammonia, water, aliphatic alcohols, and acidic compounds that ion formation in TSP may be explained by considering only the gas-phase chemistry as relevant [35–37], whereas for ionic compounds the liquid-phase chemistry is found to be predominant [38]. Other authors [39, 40] concluded that nonionic compounds tend to behave in an intermediate way, such that both gas- and liquid-phase processes contribute to ion formation. This amphibious behavior, which probably also applies to carbamates, makes it difficult to predict and explain ion formation in TSP.

This article reports a study on the influence of some parameters on the ion formation in thermospray mass spectrometry (TSP-MS) by using flow injection analysis (FIA) of 19 carbamates and 12 of their degradation products. Relevant information on all compounds is given in Table 2. The degradation products are aldicarb sulfoxide, aldicarb sulfone, and butocarboxim sulfone (from some oxime-type *N*-methyl carbamates), methiocarb sulfone, 3-hydroxycarbofuran, and its phenol, 3-ketocarbofuran and its phenol and 1-naphthol (from some aryl-type *N*-methyl carbamates), and the pirimicarb metabolites 2-dimethylamino-, 2-methylamino-, and 2-amino-6-hydroxypyrimidine. The parameters studied include two carrier streams (50:50 v/v mixtures of methanol–water or acetonitrile–water), three additives (ammonium acetate, ammonium formate, or nicotinic acid), two modes of ionization (filament- or discharge-assisted TSP), and positive or negative ion detection. Additionally, the influence of the vaporizer temperature was investigated.

Experimental

Thermospray Mass Spectrometry

Flow injection TSP-MS was performed on Hewlett-Packard 5989A ("Engine") and 5988A quadrupole mass spectrometers, coupled to Hewlett-Packard UX98578X and 59970C data systems, respectively (Hewlett Packard, Palo Alto, CA).

Full scan mass spectra were acquired with a scan range of 100–350 u, at a rate of 425 u/s, via filament- or discharge-assisted ionization. Mass spectra of the compounds were obtained by subtracting an average background spectrum from the compound spectrum at the highest point of the analyte peak. A carrier stream of a 50:50 v/v mixture of water and an organic modifier (methanol or acetonitrile) was used at a flow rate of 0.8 mL/min. Ammonium acetate or ammonium formate, in a concentration of 50 mM, or nicotinic acid (3-carboxypyridine), in a concentration of 10 mM, was used as a carrier stream additive. Flow injection was performed with 10- and 20-μL samples for positive and negative ion detection, respectively, with a HP 1090A (type 1; Hewlett Packard) liquid chromatograph with automatic injection. Directly after the injector a 30-cm-long coiled capillary was inserted to enhance mixing of the sample and the carrier stream. Stock solutions were prepared in absolute methanol or acetonitrile to prevent hydrolysis and were stored in the dark at −20 °C. Standard solutions were freshly prepared before analysis by dilution of the stock solution with water to approximately 50-μg analyte per milliliter of eluent; the solutions were injected twice. The ion source temperature was kept at 200 °C. The probe stem temperature was adjusted to obtain a stable ion current, that is, at a 90% evaporation percentage from the TSP probe. The optimal stem temperature —found to lie at 90 °C—was maintained throughout all experiments. The related probe tip temperature was approximately 170 °C.

Chemical Ionization and Fast-Atom Bombardment Mass Spectrometry

Desorption chemical ionization mass spectra were obtained on a MAT90 magnetic sector instrument (Finnigan MAT, Bremen, FRG) by using methanol or ammonia as the reagent gas. The source was kept at 150

Table 1. Ions reported for carbofuran with various ionization methods

Method (specification)[a]	Mass-to-charge ratio (relative abundance)[b,c]					Ref
CI-MS (NH_3)		222 (100)	165 (11)			11
CI-MS (CH_4)		222 (24)	165 (100)			
CI-MS (NH_3)	239 (20)	222 (100)	165 (20)		182 (5)	12
CI-MS (CH_4)		222 (40)	165 (100)			
PB-CI-MS (CH_4)		222 (100)	165 (100)			30
DLI		222 (?)	165 (?)	263 (?)		19
DLI		222 (100)		263 (4)	206 (5)	23
TSP (filament off)	239 (38)	222 (100)				18
TSP (filament off)	239 (100)	222 (67)				20
TSP (filament off)	239 (?)	222 (100)				21
TSP (filament off)	239 (55)	222 (100)		280 (18)	254 (10)	24
TSP (filament on)	239 (100)	222 (40)				28
TSP (filament on)	239 (100)	222 (25)				30
ISP		222 (100)	165 (24)			30
APCI		222 (100)	165 (64)			30

[a] PB, particle beam; DLI, direct liquid introduction; ISP, ionspray; APCI, atmospheric pressure chemical ionization.
[b] Relative abundance in comparison to the base peak (100) in percentage.
[c] ? indicates the mass-to-charge ratio reported without relative abundance.

Table 2. General information of carbamate pesticides and their degradation products used in this study

No.	Common name [CAS number]	Systematic name	MW (u)
1	aldicarb [116-06-3]	2-methyl-2-(methylthio)propanal, *O*-[(methylamino)carbonyl]oxime	190
2	aldicarbsulfoxide [1646-87-3]	2-methyl-2-(methylsulfinyl)-propanal, *O*-[(methylamino)carbonyl]-oxime	206
3	aldicarbsulfone [1646-88-3]	2-methyl-2-(methylsulfonyl)-propanal, *O*-[(methylamino)carbonyl]-oxime	222
4	aminocarb [2032-59-9]	4-(dimethylamino)-3-methyl phenol, *N*-methyl carbamate	208
5	asulam [3337-71-1]	[(4-aminophenyl)sulfonyl]carbamic acid methyl ester	230
6	barban [101-27-9]	4-chlorophenyl carbamic acid, 4-chloro-2-butynyl ester	257
7	benomyl [17804-35-2]	[1-[(butylamino)carbonyl]-1H-benzimidazol-2-yl] carbamic acid methyl ester	290
8	BDMC	4-bromo-3,5-dimethylphenyl, *N*-methyl carbamate	257
9	butocarboxim [34681-10-2]	3-(methylthio)-2-butanone, *O*-[(methylamino)carbonyl]oxime	190
10	butocarboximsulfone [34681-23-7]	3-(methylsulfonyl)-2-butanone, *O*-[(methylamino)carbonyl]oxime	222
11	carbaryl [63-25-2]	1-naphthalenol, *N*-methyl carbamate	201
12	carbendazim [10605-21-7]	1H-benzimidazol-2-yl carbamic acid methyl ester	191
13	carbofuran [1563-66-2]	2,3,-dihydro-2,2-dimethyl-7-benzo-furanol, *N*-methyl carbamate	221
14	dioxacarb [6988-21-2]	2-(1,3-dioxolan-2-yl)phenol, *N*-methyl carbamate	223

(continued)

Table 2. General information of carbamate pesticides and their degradation products used in this study (*continued*)

No.	Common name [CAS number]	Systematic name	MW (u)
15	ethiofencarb [29973-13-5]	2-[[ethylthio]methyl)phenol, *N*-methyl carbamate	225
16	3-hydroxy-carbofuran [16655-82-6]	2,3-dihydro-2,2-dimethyl-3,7-benzofurandiol, 7-*N*-methyl carbamate	237
17	3-hydroxy-carbofuran-phenol [17781-15-6]	2,3-dihydro-2,2-dimethyl-3,7-benzofurandiol	180
18	isoprocarb [2631-40-5]	2-(1-methylethyl)phenol, *N*-methyl-carbamate	193
19	3-ketocarbofuran [16709-30-1]	2,2-dimethyl-7-[[(methylamino)-carbonyl]oxy]-3(2H)-benzofuranone	235
20	3-ketocarbofuran-phenol [17781-16-7]	7-hydroxy-2,2-dimethyl-3(2H)-benzofuranone	178
21	metabolite V	2-(dimethylamino)-5,6-dimethyl-4-pyrimidinol	167
22	metabolite VI	2-(methylamino)-5,6-dimethyl-4-pyrimidinol	153
23	metabolite VII	2-amino-5,6-dimethyl-4-pyrimidinol	139
24	methiocarb [2032-65-7]	3,5-dimethyl-4-(methylthio)phenol, *N*-methyl carbamate	225
25	methiocarb sulfone [2179-25-1]	3,5-dimethyl-4-(methylsulfonyl)-phenol, *N*-methyl carbamate	258
26	methomyl [30558-43-1]	*N*-[[(methylamino)carbonyl]oxy]-etanimidothioic acid methyl ester	162
27	1-naphthol [90-15-3]	1-naphthalenol	144
28	oxamyl [23135-22-0]	2-(dimethylamino)-*N*-[[(methyl-amino)carbonyl]oxy] etanimidothioic acid methyl ester	219
29	pirimicarb [23103-98-2]	dimethyl carbamic acid, 2-(dimethylamino)-5,6-dimethyl-4-pyrimidinyl ester	238
30	promecarb [2631-37-0]	3-methyl-5-(1-methylethyl)phenol, *N*-methyl carbamate	207
31	propoxur [114-26-1]	2-(1-methylethoxy)phenol, *N*-methyl-carbamate	209

°C and ionization was performed with 150-eV electrons at an emission current of 0.2 mA.

Fast-atom bombardment mass spectra also were obtained on the MAT90 equipped with an Ion Tech (Teddington, UK) saddle field gun. Xenon was used for bombardment (at 8-kV gun voltage and 0.2-mA gun current), and glycerol was used as the matrix (with or without the addition of ammonium acetate).

Chemicals

Water ("for chromatography"), methanol (99.8%, "gradient grade for chromatography"), acetonitrile (99.8% "for chromatography"), and ammonium acetate (98%) were purchased from Merck (Darmstadt, Germany). Ammonium formate was obtained from Fluka (Buchs, Switzerland) and nicotinic acid (99%) was obtained from Aldrich Chemie (Steinheim, Germany).

Carbendazim and carbofuran (both 99%) were purchased from Riedel-de Haen (Seelze-Hannover, Germany). The pirimicarb metabolites (V, VI, and VII) were gifts from Dr. P. Cabras (Cagliari, Italy) and all other compounds were obtained from Dr. Ehrenstorfer Labor (Augsburg, Germany).

Results and Discussion

Negative ion (NI) detection gives less sensitivity than positive ion (PI) detection, except for the chlorinated carbamate barban and for 1-naphthol and the three pirimicarb metabolites. The limit of detection in the PI mode typically is 1 ng for most analytes, under full scan conditions. This is in agreement with earlier reports [20, 28, 34] and shows that PI detection is generally the best choice for analytical purposes with regard to sensitivity.

In both modes of ion detection, adduct ion formation with constituent ions of the carrier stream additives (ammonium formate, ammonium acetate, or nicotinic acid) is observed. The observation of adduct

ions in the spectra is invariantly accompanied by a lower relative and absolute intensity of quasimolecular ions and of fragment ions. Simultaneously an increase in the absolute intensity of the base peak, and hence of the sensitivity of detection, is observed.

In the following text adduct ion formation and reduced fragmentation will be discussed. For clarity of presentation, first the available reagent ions are discussed, then negative and positive ions are discussed separately, and finally the influence of the vaporizer temperature and the interdependence of sensitivity versus structural confirmation are discussed.

Reagent Ions

The reaction conditions for gas-phase ionization in TSP are best characterized by the spectra of the background, that is, of the TSP aerosol itself. These spectra reflect the experimental parameters, for example, the nebulizer and source temperature and the type of instrument. The relative abundances of the main reactant ions in the background mass spectra, obtained under various conditions, are given in Tables 3 and 4.

In most cases, the ion compositions can be attributed by straightforward considerations of ion–molecule complex formation, for example, for the cluster ions $[nA + H]^+$ and $[nA - H]^-$ and for the mixed cluster ions $[nA + mB + H]^+$ and $[nA + mB - H]^-$ (where A and B are solvent molecules). Note that ammonium acetate and ammonium formate produce almost identical PI background mass spectra.

In addition to the ion–molecule complexes, seemingly "odd" ions may result from ion–molecule reactions [36, 41–43]. Only one "odd" ion, m/z 56 with the acetonitrile–water system, has significant intensity in our background spectra. The observation that the intensity of this m/z 56 ion increases forty-fold if the acetonitrile content of the carrier stream is increased from 25 to 75% is in line with the earlier proposition [41] that this ion $C_3H_6N^+$ is formed by HCN elimination from the acetonitrile proton-bound dimer. Both the ion–molecule complexes and the odd ions are available to the analytes as a reagent.

Negative Ion Thermospray Spectra

If negative ion detection is applied without additives to the eluent, most *N*-methyl carbamates generate

Table 3. Composition and relative intensities of the main ions formed in filament-on PI/TSP-MS with 50:50 (v:v) mixtures of A = methanol–water, B = acetonitrile–water, and additives C = A + 50-mM ammonium formate, D = B + 50-mM ammonium formate, E = A + 50-mM ammonium acetate, F = B + 50-mM ammonium acetate, G = A + 10-mM nicotinic acid, H = B + 10-mM nicotinic acid

Mass (u)	Ion composition	A	B	C	D	E	F	G	H
114	$[(CH_3OH)_3 + NH_3 + H]^+$			2		10			
100	$[(CH_3OH)_2 + NH_3 + H_2O + H]^+$			2		9			
97	$[(CH_3OH)_3 + H]^+$	100						13	
83	$[(CH_3OH)_2 + H_2O + H]^+$	16						3	
82	$[(CH_3OH)_2 + NH_3 + H]^+$			67		100			
68	$[CH_3OH + NH_3 + H_2O + H]^+$			37		42			
65	$[(CH_3OH)_2 + H]^+$	42						5	
50	$[CH_3OH + NH_3 + H]^+$			100		55			
36	$[H_2O + NH_3 + H]^+$			18		5			
35	$[(NH_3)_2 + H]^+$			10		5			
18	$[NH_3 + H]^+$			10		5			
142	$[(CH_3CN)_3 + H_2O + H]^+$		18						
141	$[(CH_3CN)_3 + NH_3 + H]^+$				19		34		
119	$[(CH_3CN)_2 + (H_2O)_2 + H]^+$		72						
101	$[(CH_3CN)_2 + H_2O + H]^+$		100						2
100	$[(CH_3CN)_2 + NH_3 + H]^+$				100		100		
83	$[(CH_3CN)_2 + H]^+$		3						6
77	$[CH_3CN + NH_3 + H_2O + H]^+$				6		1		
60	$[CH_3CN + H_2O + H]^+$		15						
59	$[CH_3CN + NH_3 + H]^+$				94		26		
56	$[C_3H_6N]^+$		3						3
165	[nicotinic acid + CH_3CN + H]$^+$								100
156	[nicotinic acid + CH_3OH + H]$^+$							35	
142	[nicotinic acid + H_2O + H]$^+$							7	5
124	[nicotinic acid + H]$^+$							100	41

Table 4. Composition and relative intensities of the main ions formed in filament-on NI/TSP-MS with the solvent mixtures A–H specified in Table 3

Mass (u)	Ion composition	A	B	C	D	E	F	G	H
127	$[(CH_3OH)_3 + CH_3O]^-$	9							
113	$[(CH_3OH)_3 + OH]^-$	16							
99	$[(CH_3OH)_2 + H_2O + OH]^-$	10							
95	$[(CH_3OH)_2 + CH_3O]^-$	100							
81	$[(CH_3OH)_2 + OH]^-$	60							
67	$[CH_3OH + H_2O + OH]^-$	10							
63	$[CH_3OH + CH_3O]^-$	29							
117	$[(CH_3CN)_2 + H_2O + OH]^-$		24						
99	$[(CH_3CN)_2 + OH]^-$		18						
94	$[(CH_3CN)_2 + (H_2O)_2 + OH]^-$		11						
76	$[(CH_3CN)_2 + H_2O + OH]^-$		100						
58	$[(CH_3CN)_2 + OH]^-$		71						
53	$[(H_2O)_2 + OH]^-$		10						
137	$[(HCOOH)_2 + HCOO]^-$			9	9				
91	$[(HCOOH) + HCOO]^-$			100	100				
179	$[(CH_3COOH)_2 + CH_3COO]^-$					37	18		
119	$[CH_3COOH + CH_3COO]^-$					100	100		
163	[nicotinic acid-H + CH_3CN]$^-$								100
152	[nicotinic acid-H + CH_3OH]$^-$							12	
140	[nicotinic acid-H + H_2O]$^-$							15	5
122	[nicotinic acid-H]$^-$							100	41

fragment ions $[M - H - CH_3NCO]^-$ with a relatively low absolute abundance and all noncarbamate degradation products show a base peak for $[M - H]^-$ ions. Only the halogenated carbamates barban and BDMC show molecular anions. Identical spectra invariably were observed with either filament- or discharge-assisted ionization. The sensitivity of detection in the NI mode is nearly equal to or even better than that in the PI mode for barban and BDMC, for the pirimicarb metabolites, and for 1-naphthol.

The addition of ammonium acetate or ammonium formate results in a decrease of the fragment and quasimolecular ion intensities and, moreover, in the formation of adduct ions. This is illustrated in Figures 1–3 for propoxur, barban, and the pirimicarb metabolites, respectively.

Quasimolecular ions are absent from the spectrum of propoxur in the absence of additives (Figure 1a), whereas adduct ions $[M + CH_3COO]^-$ and their fragments (loss of CH_3NCO and C_3H_6) are observed upon addition of ammonium acetate to the carrier stream (Figure 1b). The molecular anion signal dominates the spectrum of barban without additives; chlorine and methoxy adduct ions, $[M + Cl]^-$ and $[M + CH_3O]^-$, are also present (Figure 2a). The addition of ammonium acetate favors adduct formation for barban (Figure 2b), whereas the molecular anion signal decreases (in the relative and absolute sense). For the pirimicarb metabolites (Figure 3) adduct ion formation—be it with formate or acetate—competes with quasimolecular ion formation.

It is noteworthy that the tendency toward adduct ion formation increases with a decrease in the degree of methylation of the amino group, that is, with decreasing acidity. The general tendency with NI detection is that the total ion current decreases by 1–2 orders of magnitude if additives are applied to the eluent.

Positive Ion Thermospray Spectra

Figure 4 illustrates the fact that fragment ion intensities are higher for the carbamates with discharge- than with filament-assisted ionization if PI detection is applied. The present discussion is confined to the filament-assisted spectra: the trends observed for both modes of ionization are essentially the same.

The (partial) TSP mass spectra of all compounds, with the various carrier stream compositions (and in the filament assisted ionization mode), are presented in Table 5. The spectra of benomyl and 1-naphthol are not given because benomyl decomposes in methanol and acetonitrile solutions (to give carbendazim) [44] and because 1-naphthol does not produce any significant ions even with 1-μg injections. Table 5 shows that eluent additives may have a major influence on the

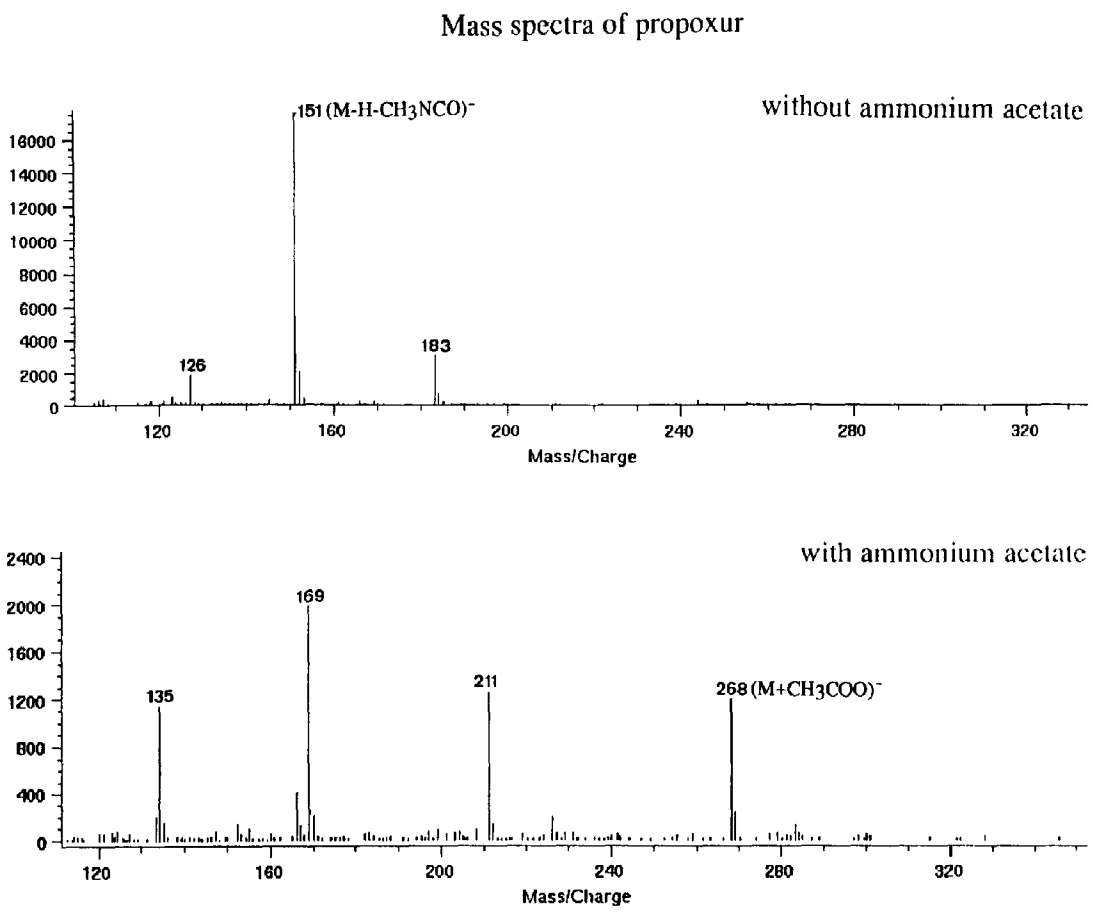

Figure 1. Filament-on NI-TSP mass spectra of 0.5 μg of propoxur (31), with 50:50 acetonitrile–water (a) without additives and (b) with 50-mM ammonium acetate as the carrier stream.

ionization process. The mass spectra of most *N*-methyl carbamates are altered completely as a result of adduct ion formation with ammonia or with nicotinic acid. However, aminocarb, carbendazim, and pirimicarb and its (noncarbamate) metabolites do not form adduct ions with the additives at all. Other authors argued that for the proton-bound dimer-type adduct ions the enthalpy of association correlates with the difference of the proton affinities (PA) of the constituent molecules [36, 45–48]. A PA difference of 30 kJ/mol has been given as the upper limit for the observation of proton-bound dimers [49]. On the basis of our data, and assuming equilibrium gas-phase chemistry, we conclude that the PA of most carbamates must be close to that of ammonia (854 kJ/mol [50]) and even closer to that of nicotinic acid (not available). The fact that complex formation occurs with most carbamates is in line with the idea [13, 17, 25] that the carbamate group provides the site of protonation. Moreover, the carbamates that do not generate complex ions (aminocarb, carbendazim, pirimicarb) have structural features that may provide a different site of protonation: a dimethyl amino group in aminocarb and an aromatic ring nitrogen in carbendazim and pirimicarb would make these compounds more basic.

The preceding suggestion about the basicity of the compounds is not in line with the fact (see Table 5) that many carbamates, including aminocarb and carbendazim, also form adduct ions with acetonitrile and methanol (PA[CH_3CN] = 787 and PA[CH_3OH] = 761 kJ/mol [50]) under TSP conditions. In contrast, we do not observe adduct ion formation of carbamates with methanol under CI conditions (with methanol as the reaction gas), whereas ammonium adducts are readily observed (with ammonia as the reaction gas). Moreover, the bond energies in methanol or acetonitrile proton-bound dimers of the carbamates would give rise to immediate dissociation of the complex ions unless these ions have a very low internal energy. It is therefore likely that acetonitrile and methanol adduct

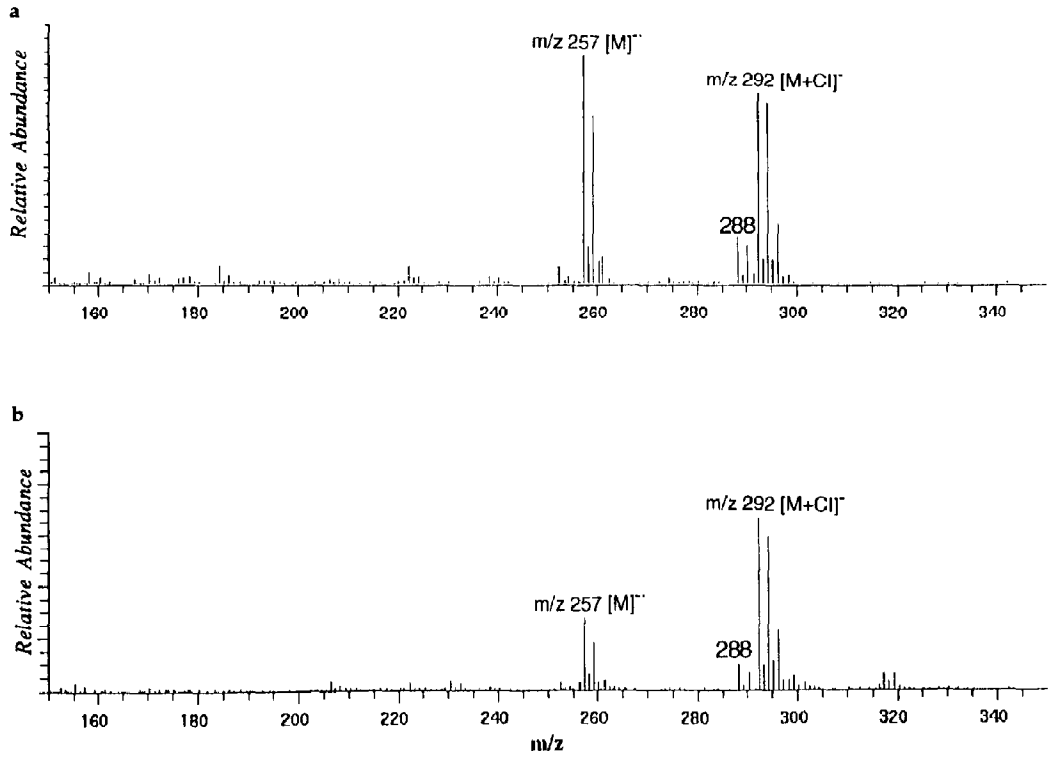

Figure 2. Discharge-assisted NI-TSP mass spectra of 1.5 μg of barban (6), with 50:50 acetonitrile–water (a) without additives and (b) with 50-mM ammonium acetate as the carrier stream.

ion formation is a result of the TSP evaporation process, where the liquid expansion may yield such "cold" ions.

The divergent behavior of the carbamates—some do not form adducts and others do so even quantitatively—implies that it is not possible to create a single set of TSP conditions to observe all carbamates by similar ions, be it $[M + H]^+$ or $[M + X + H]^+$. Although PA determinations would be helpful, the (apparent) basicity of the carbamates may be used as an extra criterion for identification.

In addition to spectrum alterations by enhanced adduct ion formation in the presence of additives, fragmentation is reduced or completely suppressed for most *N*-methyl carbamates. In general, and under CI or fast-atom bombardment (FAB) ionization as well as under TSP conditions, *N*-methyl carbamates characteristically lose methyl isocyanate (CH_3NCO) from their protonated or ammoniated molecular ions (see, e.g., ref 17 for CI; FAB spectra were recorded, but they are not discussed here). In some cases compound-specific fragmentation is observed, but the signal intensity for this type of fragmentation is generally low. However, fragmentation from the ammoniated molecules shows a lower abundance relative to that of the $[M + NH_4]^+$ ions, than does fragmentation from the protonated species (relative to the $[M + H]^+$ ions). Moreover, the nicotinic acid adduct ions do not show fragmentation at all. In principle, analyte detectability will be best if all of the available analyte molecules contribute to a minimum of different ions. Therefore adduct ion formation should either be promoted—at best up to a quantitative reaction—or be fully suppressed. The overall reduction of fragmentation can be explained by the change in available reagent ions (e.g., NH_4^+ instead of $CH_3OH_2^+$) and by a concomitant change in the tendency to form proton-bound dimers (with apparently different available fragmentation processes).

Note that the abundant fragmentation observed in ammonia CI of carbamates (see Table 1 for carbofuran; in general, fragment ion intensity with carbamates in CI is over 10% of the base peak intensity) also may be due to strong thermal dissociation of the direct CI probe or of the source at high temperatures.

The use of tandem mass spectrometry to investigate the behavior of the various ions, for example, by examining possible differences in fragment ion intensities of methanol- or ammonia-protonated carbamates, is beyond the scope of this paper.

With some *N*-methyl carbamates (e.g., butocarboxim and propoxur), $[M + 59]^+$ ions were observed when 50:50 acetonitrile–water with ammonium salt

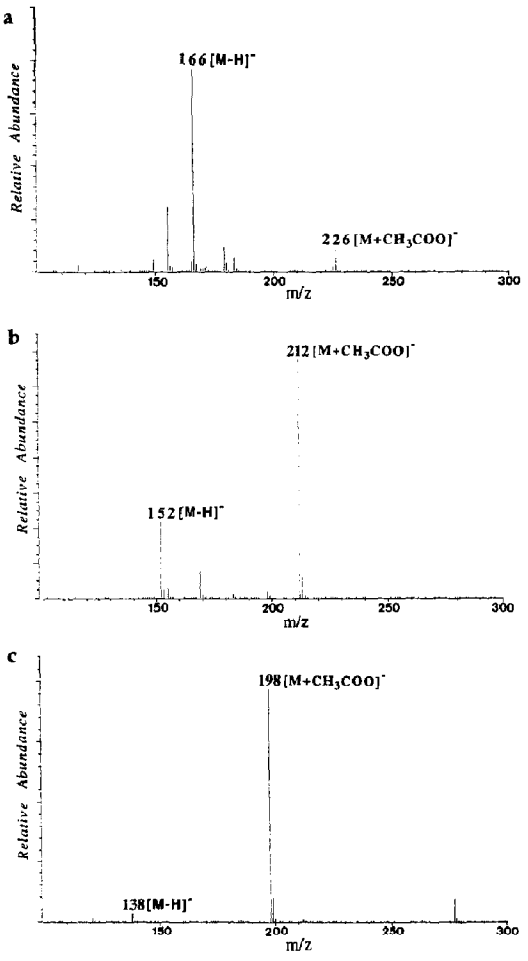

Figure 3. Filament-on NI-TSP mass spectra of 0.5 μg of the metabolites (**a**) V (**21**), (**b**) VI (**22**), and (**c**) VII (**23**) with 50:50 methanol–water that contained 50-mM ammonium acetate as the carrier stream.

additives was used. A similar observation has been reported before, and an ion–molecule reaction of protonated and neutral analyte molecules was proposed [24]. However, the $[M + 59]^+$ ions have a different origin in our case, because these ions vanish if ammonia is not present. The presence of m/z 59 in the background mass spectrum (Table 3) shows that the $[M + 59]^+$ ions probably are adducts of the type $[M + H + CH_3CN + NH_3]^+$. The formation of this complex is not understood. Its formation by a side reaction is undesirable and easily can be prevented by not using the eluent composition that gives rise to these ions. A more detailed study on the $[M + 59]^+$ ion has been published elsewhere [51].

Vaporizer Temperature

A further important parameter in LC/TSP-MS of *N*-methyl carbamates is the vaporizer temperature. A high nebulizer temperature (300–350 °C) in APCI-MS has already been given as a possible cause for relatively high fragment ion intensities [30]. Thermal degradation takes place by elimination of methyl isocyanate (CH_3NCO) from the molecule. For this reason $[M + H - CH_3NCO]^+$ ions may result from fragmentation of the protonated carbamates and from protonation of the thermal reaction products.

Therefore we tried to establish the possibility of thermal degradation by monitoring the relative intensities of $[M + H - CH_3NCO]^+$ and $[M + H]^+$ ions over a range of probe temperatures. The probe stem temperature was varied from 75 to 105 °C and a plot of the ion intensities versus this temperature (and versus the related probe tip temperature) was recorded.

The results of a typical experiment with methiocarb as the test solute are given in Figure 5. As is obvious from the ion currents, methiocarb already dissociates thermally below 90 °C.

A similar observation applies to methiocarb sulfone, whereas all other carbamates showed no sign of thermal degradation at least up to the probe stem temperature of 90 °C, which we used for the foregoing experiments.

Analyte Detectability

In the present general study on the effects of carrier stream additives, limits of detection were determined only for some compounds. The effects of carrier stream additives on the analyte detectability were derived from the change in the intensities of the base peaks, in the full scan mode and under optimal tuning, with 500-ng injections of the analyte. The extent of effects was related to spectra obtained with carrier streams without any additives. The analyte detectability in the PI mode did not change with the use of additives for asulam, barban, BDMC, 1-naphthol, and the degradation products of carbofuran.

For all other analytes the detectability increased by about 1 order of magnitude, that is, to about 1 ng, for the methanol–water–ammonium acetate system and also for the acetonitrile–water–ammonium formate system (with the exception of aminocarb, promecarb, and propoxur with the formate), as compared to the systems without additives. The other systems, that is, acetonitrile–water–ammonium acetate, methanol–water–ammonium formate, and the systems with nicotinic acid, did not show any enhancement in the analyte detectability.

Conclusions

The addition of ammonium acetate, ammonium formate, or nicotinic acid to the eluent in FIA/TSP-MS of carbamates with positive ion detection generally suppresses fragmentation in favor of adduct ion formation. The additives lead to an approximately tenfold enhancement sensitivity for positive ion detection for

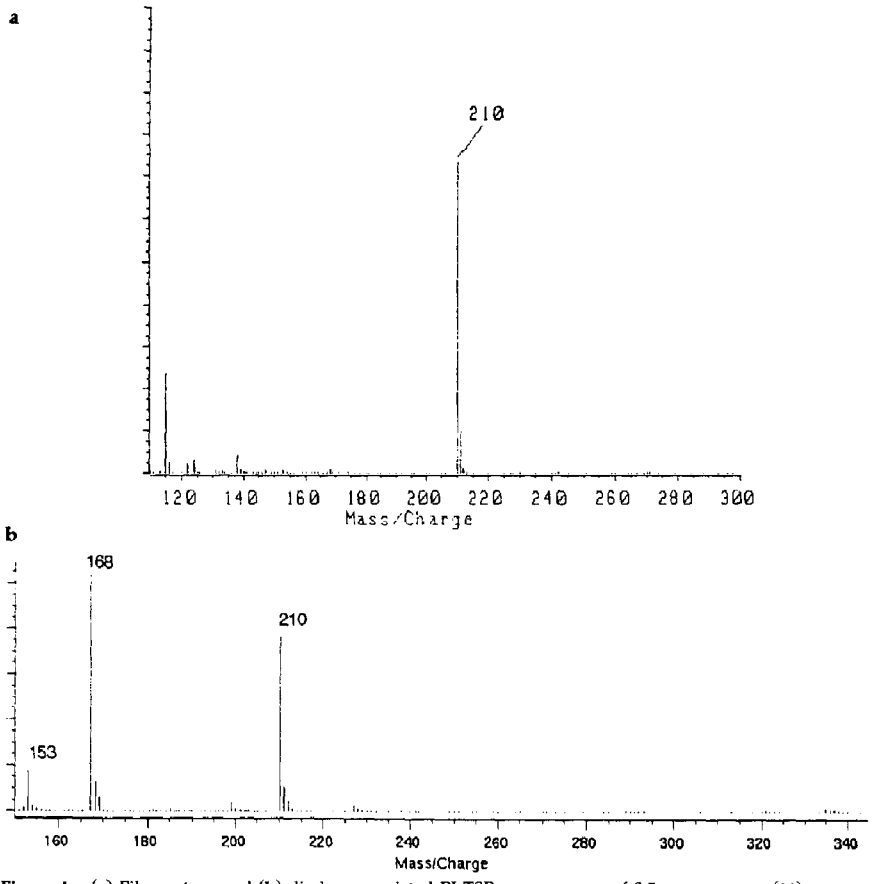

Figure 4. (a) Filament-on and (b) discharge-assisted PI-TSP mass spectra of 0.5-μg propoxur (31) with 50:50 methanol–water as the carrier stream.

the eluent systems acetonitrile–water–ammonium formate and methanol–water–ammonium acetate, but do not improve the sensitivity in any of the other systems studied. For noncarbamate-type degradation products (mostly aryl alcohols), analyte detectability is not enhanced by additives to the eluent at all. If negative ion detection is applied, the analyte detectability decreases for all carbamates studied, either because of less fragmentation or by less effective electron capture. However, the sensitivity now increases for the aryl alcohol-type degradation products with all additives.

The limits of detection attainable with FIA/TSP-MS, as extrapolated from our experimental data, are sufficiently low to allow detection of low parts per billion quantities of the *N*-methyl carbamates and most of their degradation products. A generally tenfold less sensitive detection in LC/TSP-MS, as compared to FIA/TSP-MS, may be compensated by applying on-line preconcentration techniques to 10–50 mL of surface or drinking water [52]. LC/TSP-MS therefore should be able to detect levels below those of the EEC standards for drinking water, that is, below 0.1 μg/L for the individual compounds.

Negative ion detection is best applied to the analysis of barban and the aryl alcohol-type degradation products, whereas positive ion detection with acetonitrile–water–ammonium formate or methanol–water–ammonium acetate as the eluent gives the best results for carbamate analysis with LC/TSP-MS in general.

The occurrence of thermal degradation under TSP conditions easily can be established by monitoring the quasimolecular ions of the compound of interest and its thermolysis products as a function of the probe temperature.

For the carbamates, thermal degradation under the applied TSP conditions was found to affect methiocarb and its sulfone, whereas none of the other carbamates degraded under the conditions used. Methiocarb and its sulfone therefore cannot be quantitated reliably by LC/TSP-MS.

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Table 5. Composition and relative intensities of the main ions formed from the carbamates and some of their degradation products in filament-on PI/TSP-MS with 50:50 (v/v) mixtures of A = methanol–water, B = acetonitrile–water, and additives C = A + 50-mM ammonium acetate, D = B + 50-mM ammonium acetate, E = A + 10-mM nicotinic acid, F = B + 10-mM nicotinic acid[a] (carrier stream flow-rate 0.8 ml/min)

Compound compositions	A	B	C	D	E	F
Aldicarb						
$[M+H+additive]^+$			100	100	100	100
$[M+H+modifier]^+$	30	23				
$[M+H]^+$	10	22	12	13		
$[M+H+modifier-CH_3NCO]^+$	20					
$[M+H-CH_3NCO]^+$	24	2				
$[M+H+additive-CH_3NHCOOH]^+$	100		10			
$[M+H+modifier-CH_3NHCOOH]^+$		100	33	9		
$[M+H-CH_3NHCOOH]^+$	75	61	14	6		
Aldicarbsulfoxide						
$[M+H+additive]^+$			100	100	100	100
$[M+H+modifier]^+$	20		10			
$[M+H]^+$	44	70	14	6	28	10
$[M+H+modifier+H_2O]^+$		18				
$[M+H+modifier-CH_3NCO]^+$	83	100				
$[M+H-CH_3NCO]^+$	100	68	9			
$[M+H+modifier-CH_3NHCOOH]^+$	83					
$[M+H-CH_3NHCOOH]^+$	24					
Aldicarbsulfone						
$[M+H+additive]^+$			100	100	100	100
$[M+H+modifier]^+$	79	35				
$[M+H]^+$		100	5	6		
$[M+H+modifier+H_2O]^+$		42				
$[M+H+(modifier)_2-CH_3NCO]^+$	37					
$[M+H+modifier-CH_3NCO]^+$	100	19				
$[M+H-CH_3NCO]^+$	37	14				
Aminocarb						
$[M+H+modifier]^+$		11		8		13
$[M+H]^+$	75	100	100	100	100	100
$[M+H+modifier-CH_3NCO]^+$		20				
$[M+H-CH_3NCO]^+$	100	63	2			
Asulam						
$[M+H+additive]^+$			13	45	100	
$[M+H+modifier]^+$	100					
$[M+H]^+$	52		3	18		
$[M+H+modifier+additive-58]^+$			5			
$[M+H+(modifier)_2-58]^+$		16				
$[M+H+additive-58]^+$			100	100	92	100
$[M+H+modifier-58]^+$	77	100				
$[M+H-58]^+$	14	39	4	2		
Barban						
$[M+H+additive]^+$			100	100	n.d.	n.d.
$[M+H+modifier]^+$	48					
$[M+H]^+$	95	100	6	6		
$[M+modifier+H-HCl]^+$	100					
$[M+H-HCl]^+$	75					
Benomyl						
See carbendazim						

(continued)

Table 5. Composition and relative intensities of the main ions formed from the carbamates and some of their degradation products in filament-on PI/TSP-MS with 50:50 (v/v) mixtures of A = methanol–water, B = acetonitrile–water, and additives C = A + 50-mM ammonium acetate, D = B + 50-mM ammonium acetate, E = A + 10-mM nicotinic acid, F = B + 10-mM nicotinic acid[a] (carrier stream flow-rate 0.8 ml/min) (*continued*)

Compound compositions	A	B	C	D	E	F
BDMC						
$[M+H+\text{additive}+\text{modifier}]^+$				12		
$[M+H+(\text{modifier})_2]^+$	100	100				
$[M+H+\text{additive}]^+$			100	100	100	100
$[M+H+\text{modifier}]^+$	66	90				
$[M+H]^+$	8	12	18	13		
Butocarboxim						
$[M+H+\text{additive}+\text{modifier}]^+$				6		
$[M+H+\text{additive}]^+$			100	100	100	100
$[M+H]^+$	100		34	35	7	9
$[M+H+\text{modifier}-CH_3NCO]^+$	65					
$[M+H-CH_3NCO]^+$	68					
$[M+H+\text{additive}-CH_3NHCOOH]^+$				18		
$[M+H-CH_3NHCOOH]^+$	35	100	23	14		
Butocarboximsulfone						
$[M+H+\text{additive}]^+$			100	100	100	100
$[M+H]^+$	28	100	27	14		
$[M+H+\text{modifier}-CH_3NCO]^+$	10	40			27	36
$[M+H-CH_3NCO]^+$	100	17	12			
Carbaryl						
$[M+H+\text{additive}]^+$			100	100	100	100
$[M+H+\text{modifier}]^+$	46					
$[M+H]^+$	100	100	14	9		
$[M+H+\text{modifier}-CH_3NCO]^+$	40					
$[M+H-CH_3NCO]^+$	65	50				
Carbendazim						
$[M+H+\text{modifier}]^+$		84		53	4	98
$[M+H]^+$	100	100	100	100	100	100
$[M+H-58]^+$	17	10	3	3		
Carbofuran						
$[M+H+\text{additive}]^+$			85	100	100	100
$[M+H]^+$	100	100	100	44	2	7
$[M+H-CH_3NCO]^+$	5					
Dioxacarb						
$[M+H+\text{additive}]^+$			100	100	100	100
$[M+H]^+$	100	100	32	36	8	15
$[M+H+\text{modifier}-CH_3NCO]^+$		10				
$[M+H-CH_3NCO]^+$	85	74	5			
Ethiofencarb						
$[M+H+\text{additive}]^+$			100	100	100	100
$[M+H]^+$	100	100	15	8		
3-Hydroxy-carbofuran						
$[M+H+\text{additive}]^+$			100	100	100	100
$[M+H+\text{additive}-H_2O]^+$						7
$[M+H-H_2O]^+$	100		4	3		
$[M+H-CH_3NCO]^+$	80	100	3			
3-Hydroxy-carbofuran-phenol						
$[M+H-H_2O]^+$	100	100	100	100	100	100

Table 5. *(continued)*

Compound compositions	A	B	C	D	E	F
Isoprocarb						
$[M + H + additive]^+$			100	100	100	100
$[M + H + modifier]^+$	52	73				
$[M + H]^+$	100	100	19	8		
3-Ketocarbofuran						
$[M + H + additive]^+$			100	100	100	n.d.
$[M + H]^+$			54	40		
$[M + H + modifier - CH_3NCO]^+$	50	38				
$[M + H - CH_3NCO]^+$	100	100				
3-Ketocarbofuran-phenol						
$[M + H + additive]^+$			100	100	n.d.	n.d.
$[M + H + modifier]^+$	100	70				
$[M + H]^+$	74	100				
Metabolite V						
$[M + H + modifier]^+$	4	8	1	2		9
$[M + H]^+$	100	100	100	100	100	100
Metabolite VI						
$[M + H + modifier]^+$	4	80	3	35		48
$[M + H]^+$	100	100	100	100	100	100
Metabolite VII						
$[M + H + modifier]^+$	14	100	7	71	8	100
$[M + H]^+$	100	90	100	100	100	80
Methiocarb						
$[M + H + additive]^+$			100	100	100	100
$[M + H + modifier]^+$	21	73				
$[M + H]^+$	100	100	38	19		
$[M + H + modifier - CH_3NCO]^+$	18					
$[M + H - CH_3NCO]^+$	30	20				
Methiocarbsulfone						
$[M + H + additive]^+$				100	22	100
$[M + H + modifier]^+$	13					
$[M + H]^+$				20		
$[M + H + additive - CH_3NCO]^+$			100		100	
$[M + H + (modifier)_2 - CH_3NCO]^+$	72					
$[M + H + modifier + H_2O - CH_3NCO]^+$		27				
$[M + H + modifier - CH_3NCO]^+$	91	34				
$[M + H - CH_3NCO]^+$	20	100		35		
$[H + (modifier)_2 + CH_3NCO]^+$	100					
Methomyl						
$[M + H + additive]^+$			76	60	100	100
$[M + H]^+$	11	32	100	100		35
$[M + H - CH_3SH]^+$	100	100				
$[M + H - CH_3NCO]^+$	70	3				
Oxamyl						
$[M + H + additive]^+$			100	100	100	100
$[M + H]^+$			4	5	2	
$[M + H + additive - CH_3NCO]^+$			10	5		
$[M + H + modifier - CH_3NCO]^+$	35	83				
$[M + H - CH_3NCO]^+$	100	100	10	3		

(continued)

Table 5. Composition and relative intensities of the main ions formed from the carbamates and some of their degradation products in filament-on PI/TSP-MS with 50:50 (v/v) mixtures of A = methanol–water, B = acetonitrile–water, and additives C = A + 50-mM ammonium acetate, D = B + 50-mM ammonium acetate, E = A + 10-mM nicotinic acid, F = B + 10-mM nicotinic acid[a] (carrier stream flow-rate 0.8 ml/min) (*continued*)

Compound compositions	A	B	C	D	E	F
Pirimicarb						
$[M+H]^+$	100	100	100	100	100	100
Promecarb						
$[M+H+\text{modifier}+H_2O]^+$		13				
$[M+H+\text{additive}]^+$			100	100	100	100
$[M+H+\text{modifier}]^+$	35	60				
$[M+H]^+$	100	100	19	13		
$[M+H-CH_3NCO]^+$	2	3				
Propoxur						
$[M+H+\text{additive}+\text{modifier}]^+$				10		
$[M+H+\text{additive}]^+$			100	100	100	100
$[M+H+\text{modifier}]^+$		6				
$[M+H]^+$	100	100	56	28	6	5
$[M+H-C_3H_6]^+$	9	3				
$[M+H-CH_3NCO]^+$	1	2				

[a] Carrier stream flow rate = 0.8 mL/min. n.d. = not detected.

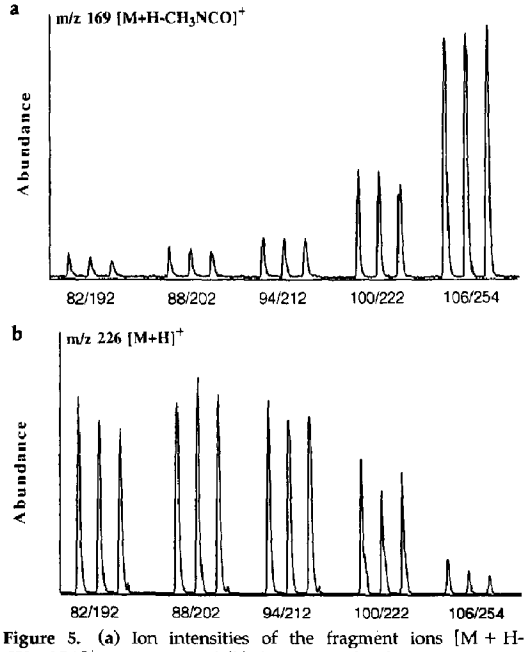

Figure 5. (a) Ion intensities of the fragment ions $[M+H-CH_3NCO]^+$, m/z 169, and (b) the quasimolecular ion, m/z 226, in PI-TSP mass spectra of 5-μg methiocarb as a function of the nebulizer temperature (stem temperature–probe tip temperatures). 50:50 methanol–water was used as the carrier stream.

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